



**University of  
Zurich<sup>UZH</sup>**

**Zurich Open Repository and  
Archive**

University of Zurich  
University Library  
Strickhofstrasse 39  
CH-8057 Zurich  
[www.zora.uzh.ch](http://www.zora.uzh.ch)

---

Year: 2013

---

## **Validation of anatomical landmarks-based registration for image-guided surgery: An in-vitro study**

Sun, Yi ; Luebbbers, Heinz-Theo ; Agbaje, Jimoh Olubanwo ; Schepers, Serge ; Vrielinck, Luc ;  
Lambrichts, Ivo ; Politis, Constantinus

**Abstract:** INTRODUCTION: Perioperative navigation is a recent addition to orthognathic surgery. This study aimed to evaluate the accuracy of anatomical landmarks-based registration. **MATERIALS AND METHODS:** Eighty-five holes (1.2 mm diameter) were drilled in the surface of a plastic skull model, which was then scanned using a SkyView cone beam computed tomography scanner. DICOM files were imported into BrainLab ENT 3.0.0 to make a surgical plan. Six anatomical points were selected for registration: the infraorbital foramina, the anterior nasal spine, the crown tips of the upper canines, and the mesial contact point of the upper incisors. Each registration was performed five times by two separate observers (10 times total). **RESULTS:** The mean target registration error (TRE) in the anterior maxillary/zygomatic region was  $0.93 \pm 0.31$  mm ( $p < 0.001$  compared with other anatomical regions). The only statistically significant inter-observer difference of mean TRE was at the zygomatic arch, but was not clinically relevant. **CONCLUSION:** With six anatomical landmarks used, the mean TRE was clinically acceptable in the maxillary/zygomatic region. This registration technique may be used to access occlusal changes during bimaxillary surgery, but should be used with caution in other anatomical regions of the skull because of the large TRE observed.

DOI: <https://doi.org/10.1016/j.jcms.2012.11.017>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-70826>

Journal Article

Accepted Version

Originally published at:

Sun, Yi; Luebbbers, Heinz-Theo; Agbaje, Jimoh Olubanwo; Schepers, Serge; Vrielinck, Luc; Lambrichts, Ivo; Politis, Constantinus (2013). Validation of anatomical landmarks-based registration for image-guided surgery: An in-vitro study. *Journal of Cranio-Maxillo-Facial Surgery*, 41(6):522-526.

DOI: <https://doi.org/10.1016/j.jcms.2012.11.017>

Manuscript Number: JCMS-D-12-00296R1

Title: Validation of anatomical-landmarks based registration for image-guided surgery: An in-vitro study

Article Type: Original Paper

Keywords: Keywords: bimaxillary orthognathic surgery, computer-assisted surgery, target registration error, cone beam computed tomography, anatomical landmark, in-vitro

Corresponding Author: Prof. Dr Constantinus Politis, MD, DDS

Corresponding Author's Institution: department of oral and maxillofacial surgery, Ziekenhuis Oost Limburg, Genk, Belgium

First Author: Yi Sun , Msc

Order of Authors: Yi Sun , Msc; Heinz-Theo Luebbbers , MD DMD; Jimoh Olubanwo Agbaje, PhD DMD; Serge Schepers, MD, DDS ; Luc Vrielinck , MD, DDS; Ivo Lambrichts, PhD, DDS ; Constantinus Politis, MD, DDS

**Abstract:** Introduction: Perioperative navigation is a recent addition to orthognathic surgery. This study aimed to evaluate the accuracy of anatomical landmark-based registration.  
Materials and methods: Eighty-five holes (1.2 mm diameter) were drilled in the surface of a plastic skull model, which was then scanned using a SkyView cone beam computed tomography scanner. DICOM files were imported into BrainLab ENT 3.0.0 to make a surgical plan. Six anatomical points were selected for registration: the infraorbital foramina, the anterior nasal spine, the crown tips of the upper canines, and the mesial contact point of the upper incisors. Each registration was performed five times by two separate observers (10 times total).  
Results: The mean target registration error (TRE) in the anterior maxillary/zygomatic region was  $0.93 \pm 0.31$  mm ( $p < 0.001$  compared with other anatomical regions). The only statistically significant inter-observer difference of mean TRE was at the zygomatic arch, but was not clinically relevant.  
Conclusion: With six anatomical landmarks used, the mean TRE was clinically acceptable in the maxillary/zygomatic region. This registration technique may be used to access occlusal changes during bimaxillary surgery, but should be used with caution in other anatomical regions of the skull because of the large TRE observed.

**Title: Validation of anatomical-landmarks based registration for image-guided surgery: An in-vitro study**

**Yi Sun, MSc<sup>1,2</sup>, Heinz-Theo Luebbbers MD DMD<sup>4</sup>, Jimoh Olubanwo Agbaje, PhD DMD<sup>1</sup>, Serge Schepers, MD DDS<sup>1,3</sup>, Luc Vrielinck, MD DDS<sup>1</sup>, Ivo Lambrichts, PhD DDS<sup>2</sup>, Constantinus Politis, MD DDS<sup>1, 2§</sup>**

<sup>1</sup>Oral and Maxillofacial Surgery, St. John's Hospital, Schiepse bos 6, 3600 Genk, Belgium.

(Head: C. Politis, Prof. MD. DDS )

<sup>2</sup>Faculty of Medicine, Hasselt University, Diepenbeek, Belgium.

<sup>3</sup>Oral and Maxillofacial Surgery, Faculty of Medicine, Gent University, Belgium.

<sup>4</sup>Clinic for Cranio-Maxillofacial Surgery, University Hospital of Zurich. Switzerland.

<sup>§</sup>Corresponding author

Prof. Dr. C. Politis

Department of Oral and Maxillofacial Surgery

St. Johan's Hospital

Schiepse Bos 6

3600 Genk

Belgium

Tel: +32 89 32 61 61

Fax: +32 89 32 17 79

Email: [constantinus.politis@uhasselt.be](mailto:constantinus.politis@uhasselt.be)

**Sources of Financial Support:**

None

## ***SUMMARY***

***Introduction:*** Perioperative navigation is a recent addition to orthognathic surgery. This study aimed to evaluate the accuracy of anatomical landmark-based registration.

***Materials and methods:*** Eighty-five holes (1.2 mm diameter) were drilled in the surface of a plastic skull model, which was then scanned using a SkyView cone beam computed tomography scanner. DICOM files were imported into BrainLab ENT 3.0.0 to make a surgical plan. Six anatomical points were selected for registration: the infraorbital foramina, the anterior nasal spine, the crown tips of the upper canines, and the mesial contact point of the upper incisors. Each registration was performed five times by two separate observers (10 times total).

***Results:*** The mean target registration error (TRE) in the anterior maxillary/zygomatic region was  $0.93 \pm 0.31$  mm ( $p < 0.001$  compared with other anatomical regions). The only statistically significant inter-observer difference of mean TRE was at the zygomatic arch, but was not clinically relevant.

***Conclusion:*** With six anatomical landmarks used, the mean TRE was clinically acceptable in the maxillary/zygomatic region. This registration technique may be used to access occlusal changes during bimaxillary surgery, but should be used with caution in other anatomical regions of the skull because of the large TRE observed.

***Keywords:*** bimaxillary orthognathic surgery, computer-assisted surgery, target registration error, cone beam computed tomography, anatomical landmark, in-vitro

## Introduction

Navigation systems are widely used in the operating room to improve surgical accuracy. In oral and maxillofacial surgery, there have been clinical reports detailing the successful implementation of navigation systems for various operations ([Lubbers et al., 2011a](#)), including implant placement ([Widmann et al., 2007](#); [Xiaojun et al., 2007](#)), trauma ([Yu et al., 2010](#); [Markiewicz et al., 2012](#)), foreign body removal ([Eggers et al., 2009a](#); [Verhaeghe et al., 2012](#)), tumor resection ([Lubbers et al., 2011c](#)), and orthognathic surgery ([Lo et al., 2010](#)).

In bimaxillary orthognathic surgery, in which the maxilla is mobilized first, an intermediate splint is used to bring the maxilla to the planned position. However, by principle the splint only allows control of occlusion in the transverse and sagittal position, the vertical position is not controlled. A number of inaccuracies can occur in the axial, frontal, and sagittal planes due to the mobility of the lower jaw, potential inaccuracies in preoperative face-bow registration, cast surgery, differences in joint impressibility, uneven manual compression by the surgeon between left and right during LeFort I intrusion (especially when dealing with asymmetries), bony interferences at the pterygoids in posterior impactions, and difficulty in maintaining manual control of a (multi-)segmented maxilla in all dimensions. Although an external pin at the base of the nose is a reference point for the evaluation of vertical positioning of the upper incisor edge, this linear length also depends on the sagittal change of the repositioned maxilla.

Due to these potential errors introduced through mandibular positioning, even a good intermediate wafer may result in inaccurate sagittal positioning, and vertical asymmetric canting of the occlusal plane. Currently available techniques to diminish these inaccuracies are non-navigational ([Schwestka et al., 1990](#); [Kretschmer et al., 2009](#);

*Fuglein and Riediger 2011*). Although navigation may be considered an additional tool to evaluate the accuracy of maxillary repositioning after Lefort I osteotomy, there have been few reports about this application.

*Hohlweg-Majert et al., 2005* state that precise registration of the system is the main precondition to attain acceptable accuracy. Different registration methods exist and can be categorized in two groups: marker-based registration and marker-free registration.

In marker-based registration: The utilization of a registration template is a well-known non-invasive method that has proven to be reliable and accurate regarding registration results (*Luebbers et al., 2008; Eggers et al., 2009a; Eggers et al., 2009b; Widmann et al., 2010; Bettschart et al., 2011*). The average accuracy of the template-based registration is between 1 to 2 mm. This device can be placed on the occlusal surface of patients, or be fixed to three intra-oral reference points (*Widmann et al., 2010*) in completely edentulous patients. However, this method has its disadvantage. To use a registration template, this device must be fabricated prior to the operation, which requires additional preparation work. In bimaxillary surgery, one potential source of error is poor stability of the registration template because of the interference of orthodontic hooks. Similarly, self-drilling screws were inserted into the maxillary or mandibular region under local anesthesia to serve as registration points (*Yu et al., 2010*). This method provides even more accurate results (*Luebbers et al., 2008*). However, the technique is invasive and requires an additional surgical procedure to place the screws prior to the operation, and in our experience causes pain and discomfort to patients.

Laser surface scanning is a commonly applied marker-free method (*Raabe et al., 2002; Schlaier et al., 2002; Marmulla et al., 2003; Marmulla et al., 2004; Hoffmann et al., 2005*). The accuracy level of the laser surface scanning usually is around 2mm

(*Raabe et al., 2002; Schlaier et al., 2002; Hoffmann et al., 2005; Lubbers et al., 2011b*).

During bimaxillary surgery, the clinical challenge is that nasal intubation is used. In this case, the patient's facial profile is modified between CBCT acquisition and the surgical procedure. *Marmulla et al., 2006* reported that a facial skin shift could reduce the mean TRE from 1.1 mm (laser scan while lying down) to 1.7 mm (laser scan while sitting up). According to these studies, surface registration accuracy is inadequate for bimaxillary surgery because of the huge mean TRE. In the previous investigations, a high-resolution laser scanner was utilized to perform surface registration in the clinical setting (*Marmulla et al., 2003; Marmulla et al., 2004*). A good registration result was achieved which was up to  $1.1 \pm 0.28$  mm. In these study, the system registered more than 100,000 cloud points of the patient's facial profile. In contrast, in other studies (*Raabe et al., 2002; Schlaier et al., 2002; Hoffmann et al., 2005; Luebbers et al., 2008*) and normal clinical settings, the Z-touch<sup>®</sup> (BrainLab, Munich, Germany), which was a laser scanner for surface registration, acquired fewer than 1000 facial points for the registration. Although a high-resolution laser scanner is able to increase registration accuracy, this device brings additional high costs and is not universally available.

According to the published reports, there is no simple and accurate method, which is able to meet the clinical requirements of bimaxillary surgery. Anatomical landmarks are a natural feature, which could be utilized for registration. A few reports concerning the registration accuracy of anatomical landmarks. *da Silva et al., 2010* reported that the use of anatomical landmark for registration was a reliable method with which to localize the junction of the transverse and sigmoid sinuses for retrosigmoid craniotomies. In his study, the registration accuracy is below 2 mm which can not satisfy the requirements of bimaxillary surgery. Other studies demonstrate that the

accuracy of anatomical landmark registration is even worse than 3 mm (*Hardy et al., 2006; Metzger et al., 2007; Lubbers et al., 2011b*). The main error source is that there are fewer definable bony landmarks on the cranium and lateral skull to be selected as registration point. Although the tips of the crowns are easier and clearly definable, in the previous investigations, there is no report concerning utilization of dentition structures as anatomical points for registration yet. Therefore, the aim of our study is to evaluate target registration error (TRE) in the context of anatomical landmark-based registration. Anatomical points on the dental occlusal and cranium region are utilized.

## **Materials and Methods**

### *Data acquisition*

A plastic skull model (type: A20. 3B Scientific GmbH, Germany) was prepared for use in this study (Fig. 1). Eighty-five target landmarks were created by drilling holes in the surface of the plastic skull model. The diameter of the drill bit was 1.2 mm to ensure that all of the target landmarks were clearly visible on the cone beam computed tomography (CBCT) scan.

The skull model was then scanned using a SkyView CBCT scanner (Cefla dental, Italy). The scan parameters were 9 inch with dentition mode. Each slice was composed of 512 × 512 pixels. The voxel size was 0.3 × 0.3 × 0.3 mm. The DICOM (Digital Image Communications in Medicine) data was imported into BrainLab ENT 3.0.0 software for surgical planning. All of the drill holes were identified and labeled as targets on the axial, sagittal, and coronal views. The following six anatomical landmarks were identified and labeled as registration point landmark: the left and right infraorbital foramina, the anterior nasal spine, the tips of the left and right upper canines, and the



mesial contact point of the left and right upper incisors (Fig. 2). Observer 1 performed the surgical planning.

#### *Data collection*

The navigation system was set up in a normal dental consultation room to avoid infra-red light interference from other electronic equipment (Fig. 3). The reference star array was firmly attached to the skull model using a headband. After the registration procedure, all 85 target labels were checked one by one using a pointer (Fig. 4).

Whenever the pointer closes on a target label (in our case the labelled drill holes) the navigation system calculates the Euclidian distance between the actual position and the target label. So whenever the pointer is positioned inside a drill hole the system provides the local TRE by calculating the distance between where it believes to be and where it actually is.

Each observer repeated the procedure five times. In total, ten registration procedures and measurements were performed. Observer 2 carefully reviewed the surgical planning and both of the two observers practiced the registration procedure three times before the study started.

#### *Data analysis*

For each target landmark, the TRE was calculated over the ten measurements. In this study, the target landmarks were categorized into four anatomical regions, which we refer to as regions A through D (Fig. 5): the tuber zone behind the infrazygomatic crest (region A); the zygomatic arch (region B); the zygoma and the anterior maxilla (region C); and the periorbital region (region D). A two-tailed Student's *t*-test was performed using MedCalc (MedCalc Software bvba, Belgium) to evaluate the difference of the mean TRE in various anatomical regions, and in the calculated mean TRE between Observer 1 and Observer 2. Statistical significance was accepted if  $p < 0.05$ .

## Results

All target landmarks were clearly visible on the CBCT images. The registration accuracies for different anatomical regions are listed in Table 1. The maximum TRE in region C was 1.6 mm, which was the lowest maximum TRE of the four anatomical regions. In the remaining three anatomical regions, the maximum TRE values exceeded 2 mm. In Fig. 6, the mean TREs for each anatomical region are presented as a box plot. Student's *t*-test showed that the mean TRE in region C was significantly lower than the TREs of the other three anatomical regions. The inter-observer difference of mean TREs was statistically significant only in region B, the zygomatic arch ( $p = 0.02$ ).

## Discussion

The accuracy of image-guided surgery depends on accurate registration. Most clinical studies have only evaluated the mean TRE. Our study also considered the maximum TRE to be a very important factor because the accuracy of the surgery is most defined by the border limit of the registration accuracy. The present study demonstrated that when anatomical landmark-based registration was used, the mean TRE in the anterior maxillary/zygomatic region was  $0.93 \pm 0.31$  mm. This result was comparable to results observed in other studies in which other registration methods were used ([Marmulla et al., 2003](#); [Marmulla et al., 2004](#); [Hoffmann et al., 2005](#); [Luebbers et al., 2008](#); [Eggers et al., 2009a](#); [Bettschart et al., 2011](#)). However, the maximum TRE was 1.6 mm, but the corresponding target landmark was located near the anterior orbital floor, above the LeFort I osteotomy line. Clinically, we considered this result to be an acceptable level of accuracy for bimaxillary surgery. Although the mean TREs in

regions A, B, and D were <1.5 mm, the maximum TREs in these regions were all >2 mm, which showed that the surgeons should take into account at least 2 mm of margin, instead of only taking the mean TRE into account.

In the previous studies, anatomical landmark registration was performed based on the following anatomical points: glabellum, bilateral lateral canthi, bilateramedial canthi, and nasal tip, which were difficult to select both virtually on the CBCT image and clinically during the registration procedure (*Hardy et al., 2006; Metzger et al., 2007*). In contrast, in our study, three anatomical points located on the occlusal level were all clearly definable, which helped improve the registration accuracy of anatomical landmarks based method. In the technique of anatomical landmarks based registration, each observer had their own preference during localizing the points. We found the anterior nasal spine and the infraorbital foramina to be an area rather than a point, which could cause human error (*Widmann et al., 2009*) or fiducial localization error (*Eggers et al., 2006*) when identifying the anatomical landmarks during surgical planning and during the clinical registration procedure. In order to minimize the difference between two observes, both observers were carefully trained three times to standardize in registration before the study started. The results of the paired t-test demonstrate that, after sufficient training, there the only significant difference of mean TRE between Observer 1 and Observer 2 was in the region of the zygomatic arch. However, a difference of 0.15 mm in mean TRE did not exert a relevant clinical influence.

*Luebbers et al., 2008* reported that the combination of a maxillary dental splint with the percutaneous insertion of only two fiducial screws on the lateral orbital rim can significantly improve registration precision: the mean TRE significantly decreased to

0.6 mm ( $p < 0.001$ ) in the periorbital region. Similarly, [Bettschart et al., 2011](#) reported that greater three-dimensional distance between registration points correlated with more precise computer navigation, mainly in the most posterior area of the cranium. In our study, three registration points were located in the occlusal surface of the maxilla, and the infraorbital foramina to the left and right of the maxilla were selected as two additional registration points to extend the volume between the registration points. However, even with the inclusion of the infraorbital foramina, we were unable to achieve a TRE that was as precise as the one reported by [Luebbers et al., 2008](#), probably because the infraorbital foramina are not as well defined as screw heads are.

[Zhang et al., 2011](#) observed that the fiducial markers should be distributed on the alveolar and cranial bone with the centroid of the markers near the study target to optimize the fiducial configuration and improve target registration accuracy. In our study, three anatomical landmarks were easily recognizable: the tips of the left and right upper canines, and the mesial contact point of the upper incisors. The target labels located in anatomical regions A, B, and D were farther away from the registration landmarks than those located in region C. This finding explains why the mean TREs in regions A, B, and D were worse than the TRE in region C. This finding also agreed with other studies ([Luebbers et al., 2008](#); [Bettschart et al., 2011](#)).

Based on recent studies, CBCT has become a commonly applied imaging modality in oral and maxillofacial surgery. [Eggers et al., 2009b](#) proved that CBCT is equivalent to CT regarding precision in image-guided maxillofacial surgery. In our study, the SkyView CBCT had a limited field of view (maximum 12 inches); therefore, the region of interest was only the midface. However, this field of view was sufficient for bimaxillary surgical planning as long as all of the anatomical regions were visible.

The anatomical landmarker-based registration as presented is a simple and non-invasive method to use for maxillary surgery because the surgeon needs to visualize these six points during the operation anyway, so no additional surgical work is required. However, for other types of surgery, the clinicians must first determine whether the 6 anatomical landmarks are to be explored during the surgery, and then determine whether the registration accuracy in the region to be operated meets the clinical requirements.

Based on the simplicity and precision of the technique we believe the next steps should be aiming to the question, which patients might possibly benefit from the procedure by the means of clinical outcome. It has been shown in the investigation of [Rustemeyer et al., 2010](#) that the quality level of orthognatic surgery is already very high based on conventional techniques. However, this study did not evaluate for the changes in transversal plane. Other clinical factors, e.g the position of dental midline and the balance of the maxillary occlusion were also not examined. Therefore it will be interesting to see if this high level can be optimized even further, especially since the TRE is an influence factor newly introduced by Computer Assisted Surgery.

## **Conclusions**

By using six anatomical landmarks, the mean TRE was clinically acceptable in the anterior maxillary/zygomatic region. This registration technique may be used for bimaxillary surgery to access occlusal changes during bimaxillary surgery. However, because of the observed large maximum TRE, clinicians should use caution when applying this registration method to the remaining anatomical regions.

## **Sources of Financial Support:**

None

**Conflict of interesting:**

None

## Reference List

1. Bettschart C, Kruse A, Matthews F, Zemmann W, Obwegeser JA, Gratz KW, Lubbers HT: Point-to-point registration with mandibulo-maxillary splint in open and closed jaw position. Evaluation of registration accuracy for computer-aided surgery of the mandible. *J Craniomaxillofac Surg*, 2011
2. da Silva EB, Jr., Leal AG, Milano JB, da Silva LF, Jr., Clemente RS, Ramina R: Image-guided surgical planning using anatomical landmarks in the retrosigmoid approach. *Acta Neurochir (Wien)* 152:905-910, 2010
3. Eggers G, Muhling J, Hofele C: Clinical use of navigation based on cone-beam computer tomography in maxillofacial surgery. *Br J Oral Maxillofac Surg* 47:450-454, 2009a
4. Eggers G, Muhling J, Marmulla R: Image-to-patient registration techniques in head surgery. *Int J Oral Maxillofac Surg* 35:1081-1095, 2006
5. Eggers G, Senoo H, Kane G, Muhling J: The accuracy of image guided surgery based on cone beam computer tomography image data. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 107:e41-48, 2009b
6. Fuglein A, Riediger D: Exact three-dimensional skull-related repositioning of the maxilla during orthognathic surgery. *Br J Oral Maxillofac Surg*, 2011
7. Hardy SM, Melroy C, White DR, Dubin M, Senior B: A comparison of computer-aided surgery registration methods for endoscopic sinus surgery. *Am J Rhinol* 20:48-52, 2006
8. Hoffmann J, Westendorff C, Leitner C, Bartz D, Reinert S: Validation of 3D-laser surface registration for image-guided cranio-maxillofacial surgery. *J Craniomaxillofac Surg* 33:13-18, 2005
9. Hohlweg-Majert B, Schon R, Schmelzeisen R, Gellrich NC, Schramm A: Navigational maxillofacial surgery using virtual models. *World J Surg* 29:1530-1538, 2005
10. Kretschmer WB, Zoder W, Baciut G, Bacuit M, Wangerin K: Accuracy of maxillary positioning in bimaxillary surgery. *Br J Oral Maxillofac Surg* 47:446-449, 2009
11. Lo J, Xia JJ, Zwahlen RA, Cheung LK: Surgical navigation in correction of hemimandibular hyperplasia: a new treatment strategy. *J Oral Maxillofac Surg* 68:1444-1450, 2010
12. Lubbers HT, Jacobsen C, Matthews F, Gratz KW, Kruse A, Obwegeser JA: Surgical navigation in craniomaxillofacial surgery: expensive toy or useful tool? A classification of different indications. *J Oral Maxillofac Surg* 69:300-308, 2011a

13. Lubbers HT, Matthews F, Zemmann W, Gratz KW, Obwegeser JA, Bredell M: Registration for computer-navigated surgery in edentulous patients: a problem-based decision concept. *J Craniomaxillofac Surg* 39:453-458, 2011b
14. Lubbers HT, Obwegeser JA, Matthews F, Eyrich G, Gratz KW, Kruse A: A simple and flexible concept for computer-navigated surgery of the mandible. *J Oral Maxillofac Surg* 69:924-930, 2011c
15. Luebbbers HT, Messmer P, Obwegeser JA, Zwahlen RA, Kikinis R, Graetz KW, Matthews F: Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery. *J Craniomaxillofac Surg* 36:109-116, 2008
16. Markiewicz MR, Dierks EJ, Bell RB: Does intraoperative navigation restore orbital dimensions in traumatic and post-ablative defects? *J Craniomaxillofac Surg* 40:142-148, 2012
17. Marmulla R, Hassfeld S, Luth T, Muhling J: Laser-scan-based navigation in cranio-maxillofacial surgery. *J Craniomaxillofac Surg* 31:267-277, 2003
18. Marmulla R, Luth T, Muhling J, Hassfeld S: Markerless laser registration in image-guided oral and maxillofacial surgery. *J Oral Maxillofac Surg* 62:845-851, 2004
19. Marmulla R, Muhling J, Luth T, Hassfeld S: Physiological shift of facial skin and its influence on the change in precision of computer-assisted surgery. *Br J Oral Maxillofac Surg* 44:273-278, 2006
20. Metzger MC, Rafii A, Holhweg-Majert B, Pham AM, Strong B: Comparison of 4 registration strategies for computer-aided maxillofacial surgery. *Otolaryngol Head Neck Surg* 137:93-99, 2007
21. Raabe A, Krishnan R, Wolff R, Hermann E, Zimmermann M, Seifert V: Laser surface scanning for patient registration in intracranial image-guided surgery. *Neurosurgery* 50:797-801; discussion 802-793, 2002
22. Rustemeyer J, Groddeck A, Zwerger S, Bremerich A: The accuracy of two-dimensional planning for routine orthognathic surgery. *Br J Oral Maxillofac Surg* 48:271-275, 2010
23. Schlaier J, Warnat J, Brawanski A: Registration accuracy and practicability of laser-directed surface matching. *Comput Aided Surg* 7:284-290, 2002
24. Schwestka R, Engelke D, Kubein-Meesenburg D, Luhr HG: Control of vertical position of the maxilla in orthognathic surgery: clinical application of the sandwich splint. *Int J Adult Orthodon Orthognath Surg* 5:133-136, 1990
25. Verhaeghe W, Schepers S, Sun Y, Orye J, Vrielinck L, Lakiere E, De Temmerman G, Politis C:



Removal of a low-velocity projectile from the base of the sphenoid sinus using navigation-guided endoscopy. *J Craniofac Surg* 23:472-476, 2012

26. Widmann G, Keiler M, Zangerl A, Stoffner R, Longato S, Bale R, Puelacher W: Computer-assisted surgery in the edentulous jaw based on 3 fixed intraoral reference points. *J Oral Maxillofac Surg* 68:1140-1147, 2010

27. Widmann G, Stoffner R, Bale R: Errors and error management in image-guided craniomaxillofacial surgery. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 107:701-715, 2009

28. Widmann G, Widmann R, Widmann E, Jaschke W, Bale R: Use of a surgical navigation system for CT-guided template production. *Int J Oral Maxillofac Implants* 22:72-78, 2007

29. Xiaojun C, Yanping L, Yiqun W, Chengtao W: Computer-aided oral implantology: methods and applications. *J Med Eng Technol* 31:459-467, 2007

30. Yu H, Shen G, Wang X, Zhang S: Navigation-guided reduction and orbital floor reconstruction in the treatment of zygomatic-orbital-maxillary complex fractures. *J Oral Maxillofac Surg* 68:28-34, 2010

31. Zhang W, Wang C, Yu H, Liu Y, Shen G: Effect of fiducial configuration on target registration error in image-guided cranio-maxillofacial surgery. *J Craniomaxillofac Surg* 39:407-411, 2011

**Table 1**

Registration accuracies **in mm** by anatomical region.

## Figure Legends

**Fig. 1.** Eighty-five target landmarks were drilled into the surface of the skull model and numbered. A navigational star array was attached to the surface of the model using a headband.

**Fig. 2.** Six anatomical landmarks were indicated in the planning software (iPlan ENT 3.0.0): the left and right infraorbital foramina, the anterior nasal spine, the tips of the left and right upper canines, and the mesial contact point of the left and right upper incisors

**Fig. 3.** The set-up of the navigation system in the testing room.

**Fig. 4.** The pointer with a two-star array.

**Fig. 5.** Three dimensional surface rendering of the skull model: Frontal and lateral view. Blue region: the tubert zone behind the infrazygomatic crest (region A); Purple region: the zygomatic arch (region B); Orange region: the zygoma and the anterior maxilla (region C); Green region: the periorbital region (region D).

**Fig. 6.** A box-plot of the target registration error (TRE) in tested regions. A, Tuber zone behind the infrazygomatic crest; B, Zygomatic arch; C, Zygoma and anterior maxilla; D, Periorbital region. The mean TRE was significantly lower in region C than in regions A, B, or D.

Table 1

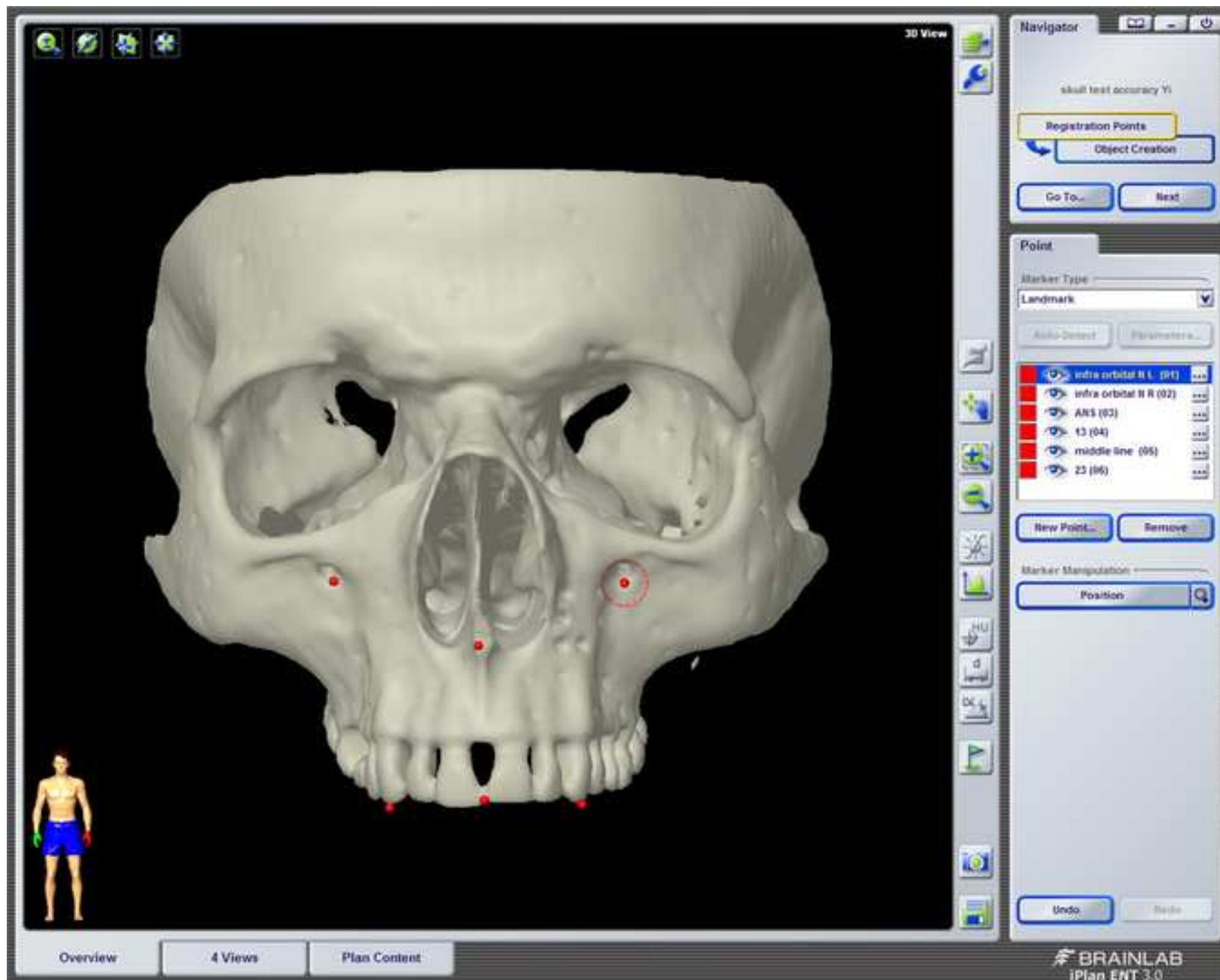
Registration accuracies in mm by anatomical region.

	Observer 1	Observer 2	Total	Inter-observer difference
<b>Periorbital</b>				
Range	0.4 - 2.2	0.4 – 2.1	0.4 – 2.2	$P = 0.08$
Mean ± SD	1.28 ± 0.39	1.21 ± 0.35	1.25 ± 0.37	
Number of target labels	29	29	29	
<b>Zygomatic arch</b>				
Range	0.5 – 2.6	0.5 – 2.1	0.5 – 2.6	$P = 0.02$
Mean ± SD	1.27 ± 0.51	1.12 ± 0.32	1.20 ± 0.43	
Number of target labels	9	9	9	
<b>Zygoma and Anterior</b>				
<b>Maxilla</b>				
Range	0.3 – 1.6	0.3 – 1.5	0.3 – 1.6	$P = 0.75$
Mean ± SD	0.95 ± 0.33	0.92 ± 0.29	0.93 ± 0.31	
Number of target labels	38	38	38	
<b>Tubert zone behind the infrazygomatic crest</b>				
Range	0.5 – 1.9	0.5 – 2.1	0.5 – 2.1	$P = 0.18$
Mean ± SD	1.13 ± 0.30	1.19 ± 0.42	1.16 ± 0.36	
Number of target labels	9	9	9	

Figure 1  
[Click here to download high resolution image](#)



Figure 2  
[Click here to download high resolution image](#)



**Figure 3**  
[Click here to download high resolution image](#)



**Figure 4**  
[Click here to download high resolution image](#)





**Figure 5**  
[Click here to download high resolution image](#)

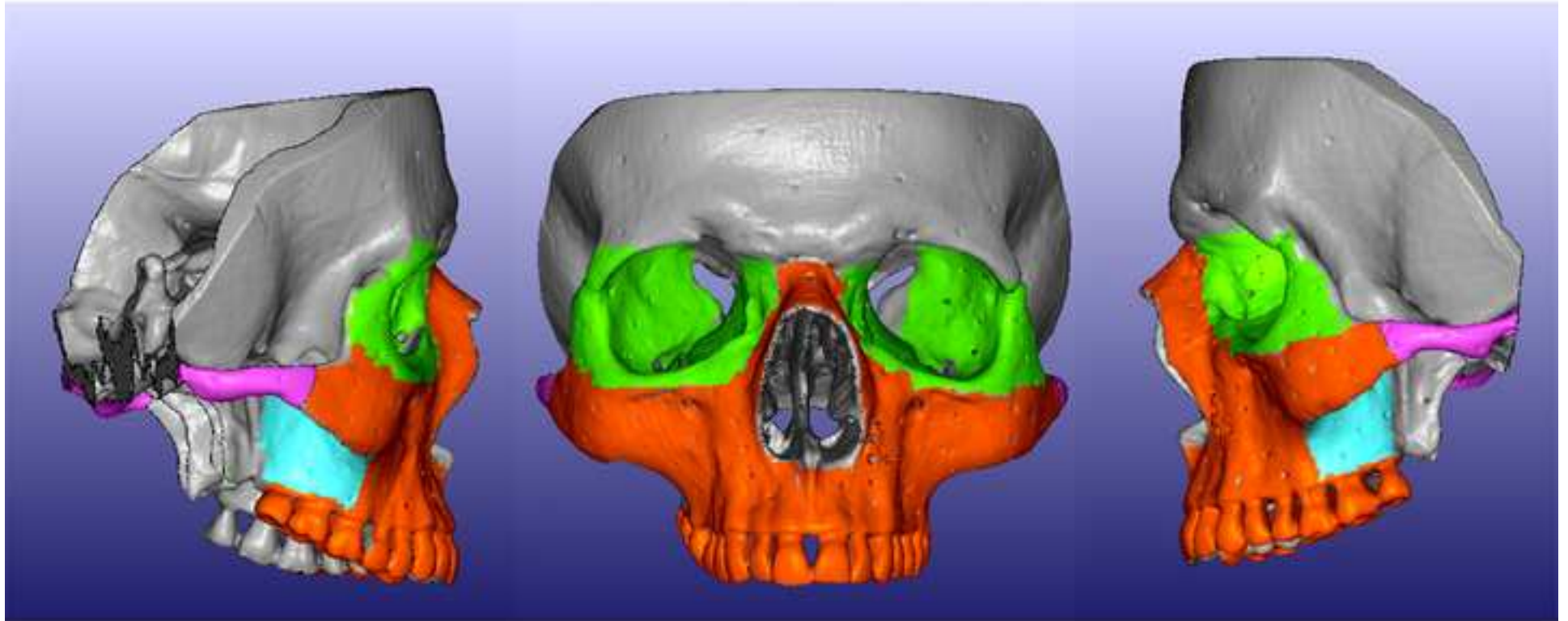


Figure 6  
[Click here to download high resolution image](#)

